Tamm plasmon polaritons: Slow and spatially compact light

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We report on the first experimental observation of Tamm plasmon polaritons (TPPs) formed at the interface between a metal and a dielectric Bragg reflector (DBR). In contrast to conventional surface plasmons, TPPs have an in-plane wavevector less than the wavevector of light in vacuum, which allows for their direct optical excitation. The angular resolved reflectivity and transmission spectra of a GaAs/AlAs DBR covered by Au films of various thicknesses show the resonances associated with the TPP at low temperatures and room temperature. The in-plane dispersion of TTPs is parabolic with an effective mass of 4×10^{-5} of the free electron mass. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2952486]

Plasmon polaritons are electronic excitations in metals or semiconductors, which allow for localization of light on a scale beyond the diffraction limit.[1–3] The localization length of light in a metal depends on its absorption coefficient and can be much less than the wavelength of light in noble metals.[4] The potential of plasmon polaritons for optical data storage as well as medical and analytical chemistry applications is very high.[5–7] A conventional surface plasmon polariton is formed with a TM polarization at the boundary of metallic and dielectric media (or vacuum).[1] The decay of the surface plasmon into the metal is the result of the metal's negative dielectric constant, while the decay into the dielectric has the same origin as in total internal reflection. The dispersion of the surface plasmon lies outside the light cone given by $k=\omega/c$, where k is the in-plane component of the wavevector of light and ω is the angular frequency, and it is for this reason that simple direct optical excitation of surface plasmons in planar structures composed of isotropic dielectric media is impossible. Although surface plasmons can be excited at metal surfaces using prisms or diffraction gratings, this approach is not always very convenient, or even practical, in experiments or device applications.

Recently, a simple planar multilayer structure has been proposed for the creation of surface waves within the light cone. It has been shown that such states can be formed at the interface between a Bragg reflector (BR) and a metal.[8] They are confined in the metal for the same reason as surface plasmons and in the BR due to the interference of light reflected by different interfaces. These states have been called Tamm plasmon polaritons (TPPs) from their analogy with the electronic Tamm states localized at crystal surfaces.[9] In contrast to a conventional surface plasmon, TPPs can be formed in both the TE and TM polarizations. Their in-plane dispersion is parabolic with an effective mass of the order of 10^{-5} of a free electron mass, and the splitting between the TE and TM polarized TPPs increases quadratically with the in-plane wavevector.[8] In this letter we report the first experimental observation of TPPs in semiconductor BRs covered with gold. We have observed the sharp resonances in reflection and transmission spectra of several samples exhibiting TPP, demonstrated their parabolic in-plane dispersion and strong spatial localization, in excellent agreement with theoretical predictions.

For the frequency interval corresponding to a passband, the eigenenergy of a TPP in a metal/BR structure can be found from the "phase matching condition"[8]

$$r_M r_{\mathrm{BR}} = 1, \tag{1}$$

where r_M is the amplitude reflection coefficient for the wave incident on the metal from the medium with refractive index n_A, and r_{BR} is the amplitude reflection coefficient of the wave incident from the medium with refractive index n_A on the BR starting with a layer of the same refractive index n_A.

The reflection coefficients r_M and r_{BR} are readily found by the transfer matrix method accounting for all layers in the structure, including the absorbing substrate and describing the refractive index of a metal using the Drude model as $n_M^2=\varepsilon_b(1-\omega_p^2/[\omega(\omega+i\gamma)])$, where ε_b is the background dielectric constant, ω_p is the plasma frequency, and γ is the plasma collision rate. For gold we take $\hbar\omega_p=8.9$ eV and $\hbar\gamma=0.027$ eV at room temperature. More details on the simulation of the TPP states including its spatial structure are given in Ref. 8. The TPP is more strongly localized than an optical mode in a semiconductor microcavity[9] because of the absence of the cavity layer and an extremely sharp decay of its electric field in the metal. Together with the parabolic dispersion, this makes the TPP an example of a spatially compact and slowly propagating photonic state.

In order to obtain evidence of the formation of TPPs experimentally, we have studied samples containing a 19 pair $GaAs/Ga_{0.1}Al_{0.9}As$ BR, with the top GaAs layer covered by gold films. The BR has been grown by molecular beam epitaxy on a GaAs substrate, and the thicknesses of the layers were chosen to provide a Bragg frequency equivalent to 1.275 eV.[10] It is essential, for the satisfaction of Eq. (1) and the formation of TPPs, that the material of the top first layer of the BR (GaAs in this case), which is adjacent to the metal, has a greater refractive index than the second layer of the BR

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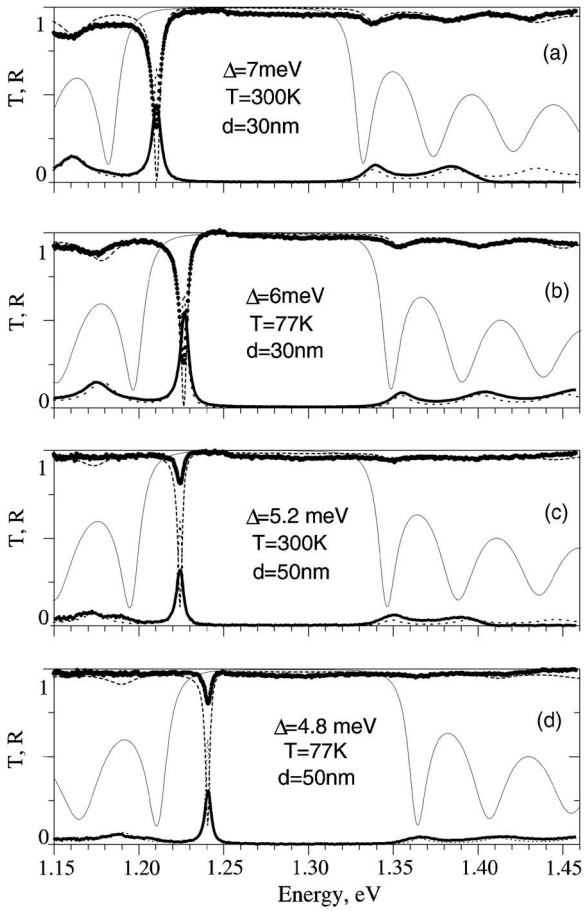

FIG. 1. Transmission and reflection spectra of GaAs/AlAs Bragg mirrors covered by layers of gold of thickness [(a) and (b)] $d=30$ nm and [(c) and (d)] $d=50$ nm taken at [(a) and (c)] 300 K and [(b) and (d)] 77 K. Circles and solid lines correspond to the measured reflection and transmission spectra, respectively; dashed and dotted lines show the calculated reflection and transmission spectra. Reflection spectra of the Bragg mirror uncovered by gold are shown by thin solid lines. Δ is the full width at half maximum of the spectral feature associated with the TPP.

$(Ga_{0.1}Al_{0.9}As)$. The substrate was transparent in the frequency region of interest in order to allow transmission measurements. Gold films with 30 or 50 nm thickness were deposited on the top of the sample.

Both reflection and transmission spectra of the samples have been measured at normal and oblique incidence of light at either room temperature or 77 K (liquid nitrogen temperature). Spectra were also modeled using the transfer matrix method using realistic parameters for GaAs, $Ga_{0.1}Al_{0.9}As$, and Au.[11,12]

Figure 1 shows the reflection and transmission spectra of the samples taken at normal incidence at different temperatures and for different thicknesses of the metal layer on the top of the dielectric BR (DBR). All sets of spectra show pronounced resonances at the frequencies corresponding to the TPP, in excellent agreement with theory. For reflection there is a dip in the reflection spectra on a background close to unity and a peak in transmission spectra where the background value is close to zero. Note that there is only one sharp transmission peak in the spectra, which makes possible the use of such a structure for the development of resonant optical filters.

The eigenenergy of the TPP depends on the thickness of the metal film.[8] For a thickness of 50 nm this almost corresponds to the case of an infinite metal, while for a thickness of 30 nm it is slightly different, as can be seen in Fig. 2.

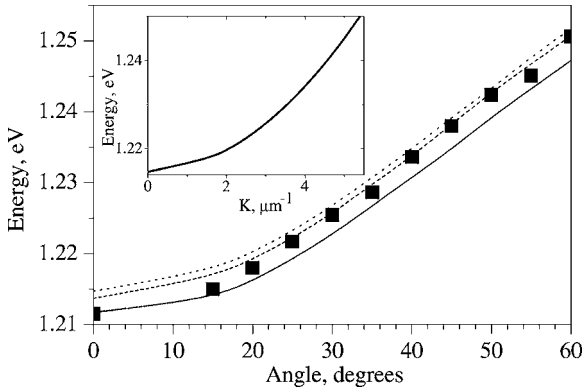

FIG. 2. The energy of the TPP resonance detected in reflection and transmission spectra measured as a function of the angle of incidence of the exciting light for the DBR covered by a 30 nm gold film (squares). The lines show the calculated TPP energies for the DBR covered by 30 nm (solid), 50 nm (dashed), and semi-infinite (dotted) gold layer thicknesses. The inset shows the extracted in-plane dispersion of the TPP state.

A decrease in the temperature leads to a decrease in the refractive indices of the material forming the BR, which in turn leads to a decrease in the optical lengths of the layers of the BR. As a result, the spectra as a whole are shifted toward higher frequencies, and due to the scaling properties of electromagnetism the phase matching condition [Eq. (1)] is satisfied at higher frequencies. Therefore a decrease in the temperature leads to a change in the frequency of the TPP.

Note that the width of the spectral feature, Δ, shown in Fig. 1, is associated with the TPP is almost identical for the experimental and modeled spectra. The value of Δ is defined by radiation decay through the gold film and BR, by absorption in the gold, and, in the case of experiment, by the roughness of the interface between the gold and the BR. A major contribution to the decay is provided by transmission through the BR. Therefore, an increase in gold thickness from 30 to 50 nm and a decrease in the plasma collision term at liquid nitrogen temperature lead only to a minor decrease in Δ.

In-plane dispersion of the observed TPP has been measured by angular resolved reflection and transmission. The data are summarized in Fig. 3. As noted in Ref. 8, the splitting between TE and TM polarized TPPs is small, less than

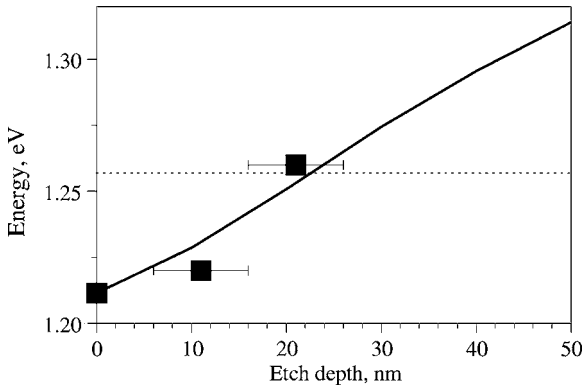

FIG. 3. The dependence of the energy of the TPP on the etch depth of the top layer of GaAs of the BR. The solid line shows the calculated dependence, while squares show the experimental results. A dotted horizontal line shows the position of the center of the photonic band gap of the BR.

the spectral width in the experiment. Consequently, the angular dependence of the eigenenergies of the TPPs was taken in unpolarized light. Very clearly, the dispersion is parabolic and can be described by an effective mass $m_{\mathrm{TPP}}=4\times10^{-5}m_0$, where m_0 is the free electron mass.

By varying the thickness of the top layer, one can change the phase of the reflection coefficient of the BR, r_{BR}, and change the frequency of the TPP. For part of the sample the thickness of the top GaAs layer was reduced by approximately 10 or 20 nm using ion etching before gold was deposited. Figure 3 shows the calculated dependence of the frequency of the TPP versus etch depth of the first GaAs layer. It can be seen that reduction of the top layer thickness leads to a shift of the TPP to a higher frequency, and when approximately 20 nm of GaAs is removed the frequency of the TPP corresponds to the center of the band gap of the BR.

In conclusion, we have obtained unambiguous experimental evidence for the existence of TPPs plasmon polaritons in planar metal-BR structures. The TPP represents a new type of light-matter mode in crystals. Contrary to the case with conventional surface plasmons, they exist within the light cone and can be directly optically excited. Due to their strong localization normal to the interface and slow in-plane motion governed by a parabolic dispersion law, TPPs represent an example of slow and compact light, which makes them a promising candidate for numerous applications in optical circuits, sensors, and other areas. Also, the observed effect can be used for the development of new types of resonant optical filters.

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